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SMAHTR – A CONCEPT FOR A SMALL, MODULAR ADVANCED HIGH TEMPERATURE REACTOR

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Abstract – *Several new high temperature reactor concepts, referred to as Fluoride Salt Cooled High Temperature Reactors (FHRs), have been developed over the past decade. These FHRs use a liquid salt coolant combined with high temperature gas-cooled reactor fuels (TRISO) and graphite structural materials to provide a reactor that operates at very high temperatures and is scalable to large sizes – perhaps exceeding 2400 MWt. This paper presents a new small FHR – the Small Modular Advanced High Temperature Reactor or "SmAHTR". SmAHTR is targeted at applications that require compact, high temperature heat sources – either for high efficiency electricity production or process heat applications. A preliminary SmAHTR concept has been developed that delivers 125 MWt of energy in an integral primary system design that places all primary and decay heat removal heat exchangers inside the reactor vessel. The current reactor baseline concept utilizes a prismatic fuel block core, but multiple removable fuel assembly concepts are under evaluation as well. The reactor vessel size is such that it can be transported on a standard tractor-trailer to support simplified deployment. This paper will provide a summary of the current SmAHTR system concept and on-going technology and system architecture trades studies.*

I. INTRODUCTION

The U.S. Department of Energy's Office of Nuclear Energy's research and development (R&D) strategy for nuclear energy [1] articulates four major R&D objectives. R&D Objective 2 states, "Develop Improvements in the Affordability of New Reactors to Enable Nuclear Energy to Help Meet the Administration's Energy Security and Climate Change Goals." This objective targets the development of enabling technologies and reactor system concepts to deliver more affordable electricity and high-temperature process heat.

Previous work at Oak Ridge National Laboratory (ORNL) [2,3,4] has identified fluoride salt-cooled high temperature reactors (FHRs) as among the most promising reactor system options for highly efficient electricity production and delivery of high-temperature process heat. These reactor concepts provide a means to address the nuclear energy R&D objectives discussed above [4].

SmAHTR (Small modular Advanced High Temperature Reactor) is a new small modular fluoride salt cooled reactor (FHR) concept developed at ORNL, that combines many of the technology elements of the Advanced High Temperature Reactor (AHTR) [2] in a compact, truck-transportable nuclear reactor system.

This paper provides an overview of the SmAHTR reactor design concept with a discussion of the design objectives, reactor configuration, and applications of the high temperature output. The current configuration of the reactor concept is a trade-off in the neutronics and thermal design along with material choices to arrive at a system that can meet the design objectives. Therefore, information is also presented in these three areas with the work representing a snapshot in the design evolution and optimization of the reactor system.

II. OVERVIEW OF THE SMAHTR DESIGN

The AHTR [2] is a large (> 1 GWe) reactor for baseload electrical power generation. In contrast, the SmAHTR evolved from a desire at ORNL to better understand the FHR design trade space on the opposite end of the applications spectrum – very small, compact, truck-transportable systems. SmAHTR design objectives include:

- Initial concept core outlet temperatures of 700ºC, with potential for future design evolutions to 850ºC and 1000ºC;
- Thermal size matched to early process heat markets (~ 100 – 125 MWt) [5];
- Passive decay heat removal capability;
- Dry waste heat rejection;
- Ability to transport the reactor module on a single semi tractor-trailer vehicle.

These design considerations were used to guide the development of the reactor system configuration discussed in the next section and supported by the neutronics, thermal-hydraulics and materials design and assessments discussed in later sections.

II.A. SmAHTR Reactor System Configuration

A baseline reactor configuration has been developed to support the design objectives. The SmAHTR reactor vessel is depicted in Fig. 1 in transport on a flatbed semi-trailer to provide a visualization of the transportability of the reactor. The reactor has an integral configuration with all key primary system components within the reactor vessel as depicted in Fig. 2. A summary of the key reactor design parameters is given in Table 1. SmAHTR's power level is 125 MWt. The primary coolant is $2LiF–BeF_2$ with the primary system pressure of approximately 1 atm. The reactor employs TRISO coated particle graphite fuel in compacts contained within removable "stringer" fuel elements positioned in hexagonal graphite core blocks. An alternative configuration based on removable fuel elements comprised of solid fuel slabs is also being considered.

The core inlet temperature is 650ºC and outlet temperature is 700ºC. During operation, SmAHTR's primary system heat is removed via three in-vessel intermediate heat exchangers (IHXs), only two of which are necessary for full-power heat removal. Similarly, decay heat is removed from the reactor primary system by three direct reactor auxiliary cooling systems (DRACS). Each DRACS employs an in-vessel salt-to-salt heat exchanger, and an ex-vessel salt-to-air heat exchanger. Natural circulation decay heat removal via the DRACS is automatically initiated upon loss of forced flow. Fluidic diodes at the outlet of the primary side of each DRACS in-vessel heat exchanger prevent unacceptable reverse flow though the heat exchanger during normal operation.

II.B. Harnessing SmAHTR's High-Temperature Heat

Small FHRs embody many desirable attributes for both electricity and process heat production. With core outlet temperatures 700ºC and higher, the systems are well matched with a variety of Brayton power conversion systems, ranging from traditional indirect helium Brayton systems, super-critical

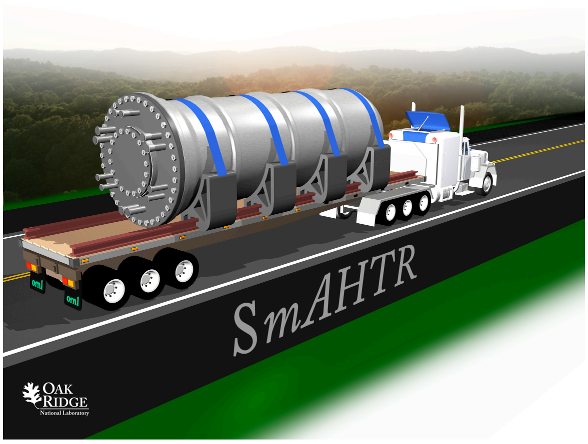


Fig 1: The SmAHTR 125 MWt reactor vessel.

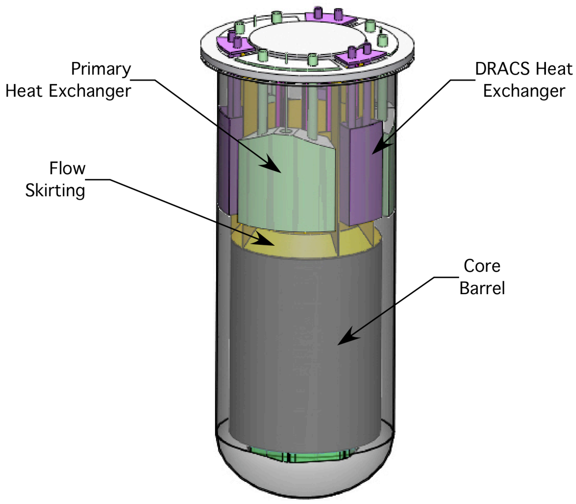


Fig 2: The SmAHTR reactor vessel internal components.

Parameter	Value
Power (MWt / MWe)	125 MWt/ ≥50MWe
Primary Coolant	2LiF-BeF_2
Primary Pressure	~1 atm
Core Inlet Temperature	650ºC
Core Outlet Temperature	700ºC
Core coolant flow rate	1020 kg/s
Operational Heat Removal	3 – 50% loops
Passive Decay Heat Removal	3 – 50% loops
Power Conversion	Brayton Cycle
Reactor Vessel Penetrations	None

Table 1: SmAHTR operating parameters.

Brayton systems, and even indirect open-cycle air Brayton systems (as operating temperatures increase). Additionally, the high volumetric heat capacity of liquid salts (approximately four times that of sodium and 200 times that of helium), coupled with high heat-transfer coefficients achievable in compact heat exchanger designs, makes FHRs extremely attractive systems for a variety of process heat applications.

Supercritical CO_2 Brayton power conversion systems appear to be a very good match for the 700ºC SmAHTR. Supercritical CO_2 enables extremely compact power conversion system architectures that are well matched to the physical size of SmAHTR. However, as noted, the initial SmAHTR concept is intended to be the basis for the eventual evolution of small FHR systems operating at 850ºC and, ultimately, as high as 1000ºC. Carbon dioxide is not feasible as a power conversion working fluid at these temperatures due to thermal decomposition. Helium and air are more suitable working fluids for these higher temperatures. As mentioned, direct cycle air Brayton systems become increasingly attractive as temperatures edge above 800ºC. All three systems are currently under consideration.

III. THE SMAHTR CORE NEUTRONICS DESIGN

The SmAHTR core neutronics configuration heavily leverages previous work performed in support of the prismatic AHTR design, particularly the use of a clustered fuel rod design contained in graphite moderator blocks [3]. The focus of the neutronics analysis to date has been the development of a reactor core model suitable for analysis of the SmAHTR fuel cycle length, power distribution, reactivity coefficients, and neutron fluence to key components, such as the graphite moderator, vessel and heat exchangers. The following sections describe the development of the neutronics model and the fuel cycle lifetime calculation.

III.A. Core Configurations

The development of the SmAHTR fuel design is based on previous studies performed at ORNL [3]. Work is on going to arrive at an optimal neutronics, thermal-hydraulics, and structural design. The entire core is replaced as a single unit (a so-called “cartridge core” design). Two “stringer” fuel concepts, in which the fuel is contained in clusters placed in the central hole of a hexagonal graphite moderator block, have been developed. These concepts are based either on solid cylindrical compacts (as in the previous ORNL studies) or annular fuel compacts. A third alternative based on fuel elements employing fueled slabs or planks is also under development.

III.A.1 Stringer Fuel Configuration

In the stringer fuel configuration, the active core consists of 19 hexagonal (45 cm pitch) fuel columns each made of five stacked graphite moderator blocks for a total core height of 400 cm (Fig. 3). The moderator block contains a central circular channel that contains the fuel cluster assembly and coolant flow channel. The solid cylindrical fuel assemby contains 72 fuel pins and (2.8-cm diameter) 19 graphite pins in a hexagonal array. The annular fuel concept has 15 fuel pins with central coolant channels and 4 graphite moderator pins. These two configurations are shown in Fig. 4. The active core is surrounded by a radial graphite reflector with an outer radius of 150 cm.

The fuel consists of 19.75% enriched uranium kernels (in $UC_{0.5}O_{1.5}$ form) in TRISO particles, which are in turn embedded in a graphite matrix

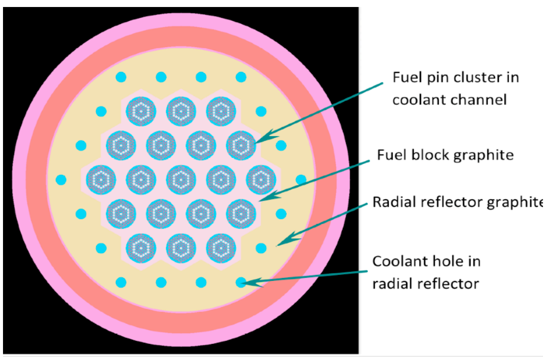
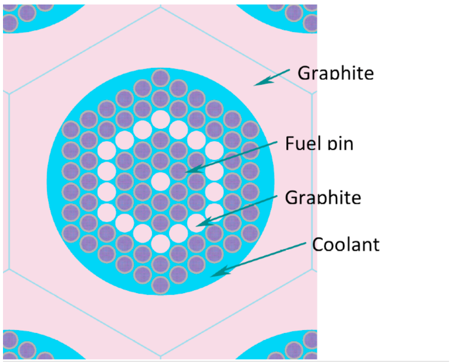
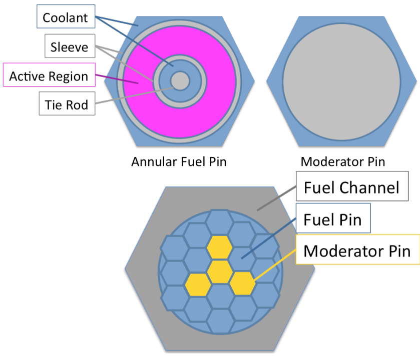


Fig 3: SmAHTR core configuration showing hexagonal arrangement of fuel stringers.



Solid Cylindrical Design Fuel Channel



Annual Design Fuel Channel

Fig 4: Solid cylindrical (top) and annular (bottom) fuel configurations.

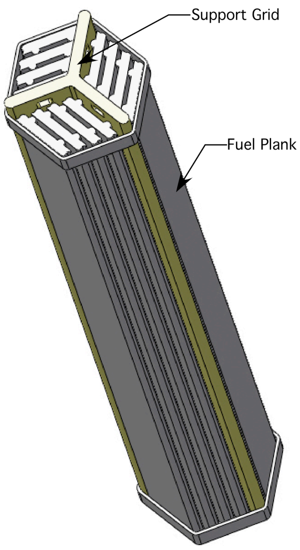


Fig 5: Alternative SmAHTR fuel concept based on fuel slab configuration.

compact. The packing fraction of the TRISO particles in the fuel compacts is 40% – 50% by volume.

III.A.2 Fuel Slab Configuration

An alternative to the solid and annular stringer fuel concept discussed above is a fuel assembly concept in which the fuel consists of solid slabs, plates, or “planks”. In this case, the TRISO coated particle graphite fuel is loaded into vertical planks at up to 40 volume percent packing fraction. The design for this concept derives from the molten salt breeder reactor moderator plank conceptual design developed in the early 1970’s [6]. The fuel planks are configured into a hexagonal grid and supported by a carbon-carbon composite internal support structure. This design has several advantages in terms of structural robustness. This approach also accommodates a larger volume of fuel in the core. An example of a fuel bundle of this design is shown as Fig 5.

III.B. Core Neutronics Analysis

Neutronics analysis has been completed for the stringer fuel designs. The evaluation of the cycle length of the SmAHTR core was performed using the three-dimensional TRITON depletion sequence in SCALE 6 [7] that uses the Monte Carlo code KENO-VI as a transport solver. Because the depletion simulation uses a multigroup formalism that involves an additional problem-dependent cross sections evaluation step (“self-shielding”), and therefore additional approximations, the initial state modeled using the multigroup formalism was first verified against a continuous energy KENO-VI calculation. It was found that the multiplication constants for the two simulations agree very well: 1.3906 ± 0.0004 for the continuous energy simulation and 1.3898 ± 0.0002 for the multigroup simulation, confirming the suitability of the multigroup processing methodology.

Analysis of three configurations were performed, two with solid cylindrical fuel compacts with packing fractions of 40% and 50% and one with an optimized annular design with a packing fraction of 50%. The results of the depletion analysis are presented in Table 2. Based on this analysis a four-year cycle can be achieved with the higher packing fraction. The annular design provides a improvement in cycle length over the cylindrical design because of an increase in fuel loading. Therefore, the current envisioned fuel cycle will consist of a whole-core replacement every four years. Note that the introduction of burnable absorbers and the use of the reactivity control system will be required to control excess reactivity. These reactivity control systems have yet to be analyzed.

Parameter	Fuel Geometry		
	Annular	Cylindrical	Cylindrical
Pitch (cm)	6.78	3.08	3.08
Kernel Diameter (μm)	500	500	425
Packing Factor (%)	50	50	40
Fuel Loading (MT)	1.76	1.54	0.99
Cycle Length (years)	4.19	3.62	2.48
Burnup (GWd/MT)	109	107	115

Table 2. Fuel parameters and cycle length analysis results.

The model was also used to estimate additional neutronic parameters of importance for kinetic and thermal-hydraulic calculations (reactivity coefficients, delayed neutron fraction, neutron lifetime), and for materials irradiation fluence estimations. The model can be further used to estimate the power distribution and additional reactivity effects (e.g., control rod worth).

IV. THE SMAHTR CORE THERMAL AND DECAY HEAT REMOVAL DESIGN

The primary focus of the core thermal-hydraulics design is to establish suitable core flow and coolant and fuel temperatures for normal operation to ensure that material limits and fuel performance limits are not exceeded. This requires the determination of the size and location of the heat exchangers and the pump flow rates. In off-normal events, the decay heat removal system must be able to remove sufficient heat to assure no fuel damage occurs. In addition to the reactor core, described in Section III, the other key components inside the vessel are the three main pumps, three intermediate heat exchangers (IHX) that remove the heat to the secondary side during normal operation and three DRACS. If forced coolant circulation stops, one-way fluidic valves at the bottom of the DRACS enable heat removal by natural convection to three outside cooling towers (one for each DRACS). Only two DRACS are required to remove the decay heat following reactor shutdown.

IV.A. Thermal-Hydraulics Model

The RELAP5-3D thermal-hydraulics code [8] has been used for SmAHTR thermal-hydraulic analysis. The version of the code employed for these analyses has the properties of a limited number of liquid salts [9]. The primary coolant salt is FLiBe (2LiF-BeF_2). The current RELAP5 model of the core includes the 19 assemblies (with flow areas of the cylindrical fuel compact stringer fuel design) in 3 core rings, with one, six and 12 assemblies in each ring respectively, from center to periphery. The core is also subdivided into ten axial nodes with a cosine power distribution. The three IHXs and the three DRACS are also modeled by RELAP5. Each DRACS is designed to remove 0.43 MW of power under natural convection conditions. The model for a single DRACS system includes three natural convection loops: one in the core, the DRACS loop with the hot side inside the vessel and the cold side inside the cooling tower, and the air natural convection loop in the cooling tower. The FLiNaK salt (LiF-NaF-KF) is used in the IHX loops and NaF-ZrF_4 salt is used in the DRACS loops. A schematic of the RELAP5 model is given in Fig. 6. Normal and off-normal operation have been simulated with RELAP5.

IV.B. Thermal-Hydraulics Analysis for Normal Operation

During normal operation at full power (125 MWt), the DRACS are inactive, and forced convection through the core takes place with the three main pumps operating. A total flow of 1020 kg/s circulates through the whole core. Full power operation with only two main pumps (out of three) is also possible. A maximum fuel temperature of 1178ºC is calculated at the mid-plane of the center pin in the center assembly, which has the highest power of the core.

IV.C. Thermal-Hydraulics Analysis for Off-Normal Operation

A loss of forced cooling (LOFC) with scram transient was simulated, with reactor power falling to decay heat levels and heat removed by the DRACS. Fig. 7 depicts the coolant temperatures calculated by RELAP5 for this transient. Natural convection flows of ~24 kg/s were calculated for the whole core with only two DRACS operating. The maximum temperature of the primary coolant was calculated to be 727°C at seven hours into the transient. This transient appears to be rather benign. This RELAP5 model is being used to study other transients such as the LOFC without scram and to perform other parametric studies and further refinements of this reactor concept.

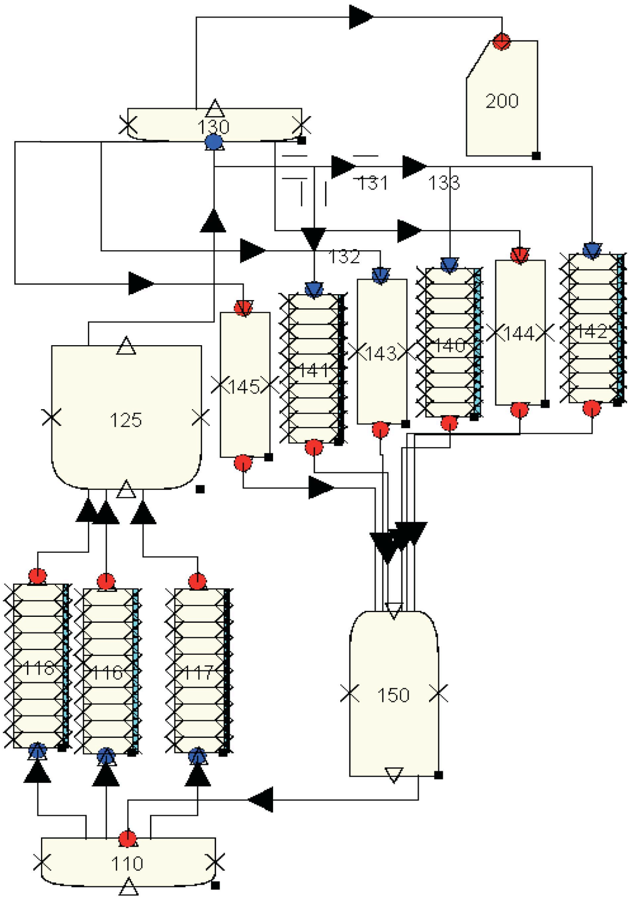


Fig 6: The SmAHTR RELAP5-3D mode (the lower plenum, core with three rings, and upper plenum on left; the three main pumps, three IHXs, three DRACS, and downcomer on right).

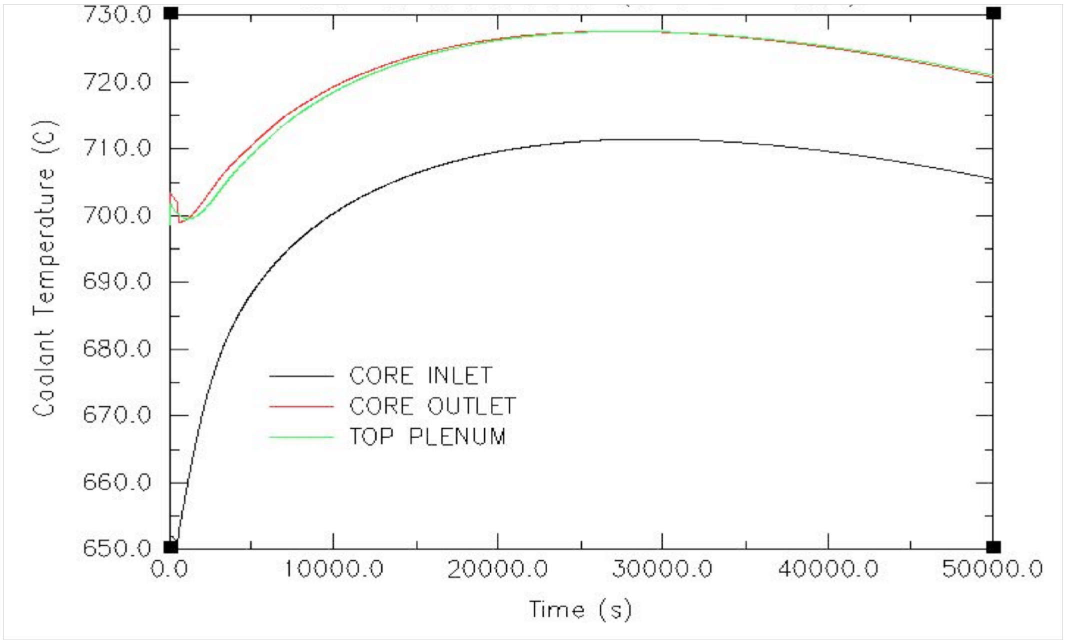


Fig 7: RELAP5-3D calculated temperature of coolant in primary system after a LOFC.

V. ASSESSMENT OF MATERIALS FOR SMAHTR

The plausible operating temperatures for fluoride salts span the range from approximately 500°C to well over 1000°C, depending on the specific salt under consideration (the liquidus temperature of the FLiBe coolant selected for SmAHTR ranges from 459°C to 1430°C). Thus, FHR operating temperatures are primarily constrained by the performance limits of the materials of construction. These structural materials must present adequate strength, toughness, corrosion resistance, and irradiation tolerance at both normal and off-normal conditions. An assessment of the materials of construction for the SmAHTR primary and secondary system was performed.

The majority of uncooled metallic components for the 700°C outlet design (RPV, core barrel and other metallic internals, IHXs, DRACS), are expected to employ Hastelloy-N. Hastelloy-N is a nickel-base alloy (Ni-7Cr-16Mo-1Si) developed at ORNL explicitly for containing high-temperature liquid fluoride salts. It is currently codified for use under ASME Boiler and Pressure Vessel Code Section VIII under Code Case 1315 for use in pressure vessels up to 704°C, but is not explicitly approved for nuclear construction within ASME's Section III. Notwithstanding, Hastelloy-N has adequate strength and excellent salt and air compatibility up to 704°C and has been successfully

Component	**Outlet Coolant Temperature**		
	700°C	**850°C**	**950-1000°C**
Graphite internals	Toyo Tanso IG110 or 430	Toyo Tanso IG110 or 430	Toyo Tanso IG110 or $30
RPV	Hastelloy N	Nickel weld-overlay cladding on 800 H, insulated low alloy steel, new nickel-based alloy	Interior insulated low alloy steel
Core barrel & other internals	Hastelloy N	C-C composite, new nickel-based alloy	C-C or SiC-SiC composite, new refractory alloy
Primary heat exchanger	Hastelloy N	New nickel-based alloy, double sided nickel cladding on nickel-based superalloy, e.g., 617 or 230	C-C or SiC-SiC composite, monolithic SiC
DRACS	Hastelloy N	New nickel-based alloy, double sided nickel cladding on nickel-based superalloy, e.g., 617 or 230	C-C or SiC-SiC composite, monolithic SiC
Pump	Hastelloy N, Ti-mod Hastelloy N	Molybdenum alloy or ceramic coated nickel-based superalloy	Molybdenum alloy or ceramic coated nickel-based superalloy
Control rods and internal drives	C-C composites, Hastelloy N, Nb-1Zr	C-C composites, Nb-1Zr	C-C composites, Nb-1Zr
Secondary loop piping	Interior insulated low alloy steel, Hastelloy N	Interior insulated low alloy steel, new nickel-based alloy	Interior insulated low alloy steel
Secondary heat exchanger (salt to salt)	Hastelloy N	New nickel-based alloy, limited permeability C-C composite	Limited permeability C-C composite
Secondary heat exchanger (salt to gas)	Coaxially extruded tubes, 800H with nickel layer	New nickel-based alloy, coaxially extruded tubes, 800H with nickel layer, limited permeability C-C composite	Unknown at this time, due to very high strength requirements at this temperature

Table 3. Leading candidate materials for various components of the SmAHTR at a range of outlet temperatures.

used in construction of both of the molten salt reactors developed at ORNL [10]. Thus the initial SmAHTR concept evolution is constrained to operate at 700°C, primarily based on the performance limits of Hastelloy-N. Depending on future progress in the development of compatible high-temperature materials, subsequent FHRs could operate with core coolant outlet temperatures up to 850°C and perhaps even 950-1000°C.

Raising the outlet temperature above 700°C will preclude the use of Hastelloy-N for most uncooled components, because its high-temperature strength drops precipitously above that temperature. Potential structural materials for higher temperatures include nickel-clad or weld overlaid superalloys, such as alloys 800H, 617, or 230, in the near term; or newly-developed, higher-strength nickel-base alloys; or even refractory metal base alloys, in the longer term. Alternatively, the use of carbon-carbon or SiC-SiC composites or monolithic SiC would allow for uncooled components to temperatures up to and beyond 1000°C. However, a major effort will be required to develop, code-qualify, and license designs that employ these advanced. Yet another material solution for some components such as the RPV or piping in the SmAHTR at a range of temperatures would be to use insulation on the internal (salt) side of the structure. This approach might facilitate the of simple low-alloy steels, though at the cost of potentially greater system complexity and monitoring requirements.

The graphite core structure of the current baseline SmAHTR is expected to be comprised of fine-webbed prismatic blocks, requiring the use of a high-strength, fine-grained graphite. Two grades of Toyo Tanso graphite (IG110 or 430) that are currently being qualified for use in high-temperatures gas-cooled reactors, such as the Next Generation Nuclear Plant, would be good candidates.

Based on these considerations, leading candidate materials for various components of the SmAHTR at three specific design output temperatures have been developed and are summarized in Table 3.

VI. CONCLUSIONS

Based on previous work on the AHTR concepts involving large designs (> 1 GWe) and the current SmAHTR concept development work, fluoride salt-cooled reactors show great promise for applications over a wide size/output range suitable for a variety of electricity and process heat production. A preliminary pre-conceptual 125 MWt SmAHTR design has been developed that is easily transportable, provides high temperature heat to support high thermal efficiency electricity generation or process heat applications, and operates within the margins of existing TRISO fuel technology.

On going design trade studies for the SmAHTR concept include an optimization of the fuel element and core configuration, assessments of the material lifetimes for major structures and components, assessment of the cost and economics of small FHRs, coupling the SmAHTR to power conversion process heat systems, and the determination of technology development needs. The results of these trade studies and a more complete description of the SmAHTR concept is available in Reference 11.

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